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Towards integrated performance evaluation of future packaging for fresh produce in the cold chain

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Abstract

Optimising ventilated packaging for fresh horticultural produce will play a key role in making future food cold chains more energy-smart and resource-efficient in a cost-effective way. Package performance analysis currently lacks an integrated approach for simultaneous and quantitative evaluation of product cooling rate, box ventilation, product quality and shelf life, box mechanical strength and energy consumption of the ventilation system. This article provides an overview of recent research on these package functionalities and summarises the performance parameters used to quantify them. Novel developments in experimental and computational tools are highlighted and various trade-offs encountered in package design are illustrated with case studies. Future perspectives point towards a more holistic evaluation of packaging throughout the entire cold chain.

Keywords: package; CFD; container; fruit and vegetables; airflow; energy; integrated

1. Introduction

For fresh horticultural produce such as fruits, vegetables and cut flowers, temperature is the single most important environmental factor affecting product deterioration rate and postharvest life (Robertson, 2013; Thompson, Mitchell, Rumsey, Kasmire, & Crisosto, 2008). Rapid removal of field heat after harvest through cooling and maintaining optimum product temperature throughout the supply chain are thus of key importance. In this way, the cold chain helps to preserve product quality and extend shelf life, thereby reducing postharvest food losses. Postharvest losses and waste in the fruit and vegetable supply chain can be as high as 13 to 38 %, before even reaching the consumer (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011). Also, up to 20 % of all perishable foods may be lost due to lack of (appropriate) refrigeration infrastructure or access to energy (IIR, 2009). A huge amount of natural resources, such as energy and water, are embodied in these food losses, but also carbon dioxide emissions (Masanet, Worrell, Graus, & Galitsky, 2008; Thompson, Mejia, & Singh, 2010). This embodied energy accounts for approximately 38 % of all energy consumed in the food industry (FAO, 2011; Gustavsson et al., 2011). The latter even equals 30 % of the world's energy consumption (FAO, 2011), and 8 % of the electrical energy use in this industry is for refrigeration (Zilio, 2014). Future cold chains for fresh produce should therefore be made more sustainable in terms of being more resource-efficient and energy-smart, but also by maintaining product quality, extending shelf life and reducing food losses (Opara, 2010). In this way, the full potential of the cold chain can be exploited to mitigate food, energy and resource insecurity.

Improving fresh-produce packaging is one of the most effective ways to address these important technological, economic and developmental challenges. The reasons are the high impact of packaging on the quality and shelf life of the product, the relatively low cost of packaging and the ease of altering its design (Defraeye et al., 2014; Galić, Ščetar, & Kurek, 2011). Packaging is also one of the few flexible elements in the cold chain that is not overly subject to regulations, standardisation and legislations. Nevertheless, their design, size and footprint are strongly dictated by the wholesalers, which thus have a considerable impact on the packaging industry. Fresh horticultural produce is predominantly packed in ventilated fibreboard boxes (Little & Holmes, 2000; Opara & Mditshwa, 2013; WPO, 2008), but also in plastic or wooden boxes, and in smaller consumer packages such as plastic clamshells, which are all stacked on pallets. Although these individual boxes are considered to be the basic level of packaging, other scales of packaging include internal packaging, such as trays, polyliner bags or punnets (Ngcobo, Delele, Opara, Thiart, & Meyer, 2013; Ngcobo, Delele, Opara, Zietsman, & Meyer, 2012; Ngcobo, Opara, & Thiart, 2012), or thermal (Moureh, Laguerre, Flick, & Commere, 2002) and mass-transfer-limiting (Pelletier, Brecht, Nunes, & Emond, 2011) pallet covers.

Packaging serves a multifunctional purpose. It should protect against mechanical damage to the produce during handling, storage and transport (Pathare & Opara, 2014). In addition, packaging should promote rapid (pre)cooling to quickly remove the field heat and thereby obtain a high throughput, but also uniform cooling of individual products is required. Furthermore, proper cooling and box ventilation are essential during transport in refrigerated containers or trucks and storage in cold stores to remove the respiration heat, hence avoiding hot spots, and to facilitate exchange of metabolic gasses such as oxygen, carbon dioxide and ethylene. Packaging should maintain product quality and enhance shelf life, for example by minimising transpiration-induced moisture loss and the resulting shrinkage (Maguire, Banks, & Opara, 2000) but also by avoiding product loss due to physiological disorders and diseases such as chilling injury. Finally, the produce-packaging system preferably has a low resistance to airflow to limit the required power and associated energy usage of ventilation systems (operational cost) during precooling, storage or transport. However, exploiting packaging design as a cost-effective energy-saving strategy has been virtually unexplored (Defraeye et al., 2014; Thompson et al., 2010). Many researchers focussed on several of these aspects of package performance, by relying on laboratory experiments, full-scale in-situ experiments or numerical simulations (e.g., with computational fluid dynamics, CFD). A non-exhaustive summary of recent work over the past decade is given in Table 1, split up according to the different functionalities of a package.

Despite this vast amount of research on package design for fresh horticultural produce, past studies mainly concentrated on a single unit operation in the cold chain (mostly precooling) or on only one or a few particular functionalities of the package, such as the cooling performance. Often conflicting package design requirements appear when multiple cold-chain unit operations or different functionalities are targeted simultaneously. A typical example is how increasing the box vent area can improve cooling rate, cooling uniformity and box ventilation but compromises mechanical strength, particularly for carton boxes (Frank, 2014; Pathare & Opara, 2014; J. Singh, Olsen, Singh, Manley, & Wallace, 2008). Similarly, a higher airflow rate enhances the cooling rate but can induce more chilling injury, moisture loss and a higher fan energy consumption. Also, a package optimised for horizontal precooling does not necessarily perform well under vertical airflow occurring during transport in a refrigerated container. Although some of these trade-offs have been explored (Baird, Gaffney, & Talbot, 1988; de Castro, Vigneault, & Cortez, 2005b; Pathare, Opara, Vigneault, Delele, & Al-Said, 2012), these efforts only scratched the surface.

To identify and minimise these numerous trade-offs, future research on ventilated packaging performance and design requires a more integrated approach. Only by such a simultaneous assessment of all its functionalities across all cold chain unit operations, the true complexity of the problem can be captured. As an important step towards such integrated evaluation, this review synthesises how each package functionality can be characterised and identifies what the most commonly-used performance parameters (PPs) are to do this in a quantitative way, for example by means of the seven-eighths cooling time. Such quantitative parameters are essential for multivariate comparison of existing designs, through simultaneous evaluation of these PPs. PPs can be used by computer-aided optimisation methods to improve package design but also cold chain design, operation and control (Banga, Balsa-Canto, & Alonso, 2008; Banga, Balsa-Canto, Moles, & Alonso, 2003). Such a comprehensive overview of the available

PPs is still lacking, to the best knowledge of the authors, and is one of the main merits of this review. In addition, recent developments in experimental tools and numerical methods to quantify these package functionalities are reviewed. Finally, trade-offs appearing in packaging design are illustrated based on research performed by the authors for the citrus cold chain. This review should guide researchers and practitioners towards more integrated and quantitative evaluation of ventilated packaging of various sizes (from bulk boxes to small consumer packaging) for the fresh-produce supply chain. As this review particularly targets ventilated packaging, it does not deal with modified atmosphere packaging. In addition, food safety is also not explicitly targeted since it is less of an issue for fresh horticultural produce than for meat or fish. Rots or insect infestation are considered to be food quality aspects in this review. Food safety thereby mainly implies chemical safety (e.g. pesticides) which is usually not considered in the context of packaging design and evaluation.

2 The design space

The performance of packaging is dependent on the specific case that is studied, which is determined by a multitude of variables and conditions. A non-exhaustive summary of the complexity of this design space is given in Figure 1. This framework needs to be identified and delineated for a specific cold chain before embarking on performance evaluation or optimisation of package designs. Several of these inputs can be set either as design variables or as constraints.

3 Package functionalities & performance parameters

In Table 2, the most relevant package functionalities and corresponding package performance parameters (PP) are summarised, and are reviewed below. PPs are essentially variables to quantify a specific functionality in a unique way. Although these functionalities and PPs will be specified at a single box level in this review, they can be defined as well at the level of a pallet, container and cold store, or for internal packaging.

The main merit of these PPs is that they enable to quantitatively compare existing package designs for each of the functionalities separately or for multiple ones at the same time. Also new designs can be evaluated in a more integrated way. Package functionalities can also be combined and translated to more general concepts, such as fruit marketability (shelf life, off-spec products, grading based on fruit quality, consumer acceptance, etc.) or process economics (profit, operational costs, product losses from waste and off-spec products, embodied water, energy or carbon dioxide emissions in the losses, etc.).

3.1 Product cooling

3.1.1 Cooling time and rate

Quantifying the cooling time and rate is particularly relevant for precooling, as this determines how fast the field heat can be removed (Brosnan & Sun, 2001). These quantities do not only affect product quality and shelf life, but also the actual time the precooling equipment needs to run, and thus the related operational costs and total product throughput.

Cooling behaviour of horticultural products

Product cooling is usually evaluated by the fractional unaccomplished temperature change *Y(t)*, which is determined from the temperature-time profile of the internal product (pulp) temperature (T_p [°C]):

$$Y = \frac{T_p - T_a}{T_{p,0} - T_a} \tag{1}$$

$T_{p,0}$ and T_a ([°C]) are the initial product temperature and the set cooling air temperature, respectively. Different temperatures T_p can be used to define *Y*: (1) the pulp temperature in the centre of the product ($T_{p,c}$), which is often measured in field or laboratory experiments since the sensor is placed there; (2) the average product temperature of an entire fruit ($T_{p,avg}$), which can be obtained from numerical modelling (CFD); (3) the surface temperature at the product-air interface ($T_{p,s}$), which is, incidentally, rarely used. The choice of T_p critically affects the value of *Y*, as typically $T_{p,c}>T_{p,avg}>T_{p,s}$ during cooling.

Newton's law of cooling can be used to estimate the core and average product temperatures (thus $Y_{p,c}$ and $Y_{p,avg}$), via an exponentially decaying function over time *t* (Thompson et al., 2008):

$$Y_{p,s} = Y_{p,c} = Y_{p,avg} = e^{-Ct} \tag{2}$$

where *C* is the cooling coefficient. This equation however assumes no large temperature gradients within the product ($T_{p,s} \approx T_{p,avg} \approx T_{p,c}$) and heat transport properties that are independent of temperature. As temperature gradients are present in horticultural products ($T_{p,c}>T_{p,avg}>T_{p,s}$), due to their limited thermal conductivity, there is a time-lag between the onset of cooling and the exponential decay of the cooling curve. The cooling curve can be split up in two parts, which gives for $Y_{p,c}$ (ASHRAE, 2010):

$$\begin{aligned} Y_{p,c} &= 1 \qquad && je^{-Ct} \geq 1 \\ Y_{p,c} &= je^{-Ct} \qquad && je^{-Ct} < 1 \end{aligned} \tag{3}$$

where *j* is the lag factor. Values of *Y* larger than 1 are not possible and there is actually a smooth transition between these two curves, so no discontinuity as Eq. (3) suggests. The lag factor is dependent on the size and shape of the product, the location in the product where the temperature is evaluated ($T_{p,c}$, $T_{p,avg}$ or $T_{p,s}$) and the Biot number (ASHRAE, 2010). This lag factor varies between 1 and 2, when based on $T_{p,c}$ (ASHRAE, 2010; Brosnan & Sun, 2001).

Cooling time

The cooling time is evaluated based on the dimensionless cooling curve *Y(t)* by determining the half cooling time (HCT, $t_{1/2}$ [s]) or seven-eighths cooling time (SECT, $t_{7/8}$ [s]) (Table 1). These are the times required to reduce the temperature difference between the product and the cooling air by half (Y = 0.5) or seven eighths (Y = 0.125). Note that their magnitude critically depends on the choice of T_p to define Y (Eq. (1)). In experiments, the determination of Y can be complicated as the set temperature (T_a) is often not constant over time due to oscillations in the refrigeration system.

The SECT is frequently applied in commercial forced-air precooling (FAC) operations since then the fruit temperature is acceptably close to the required storage temperature and the remaining heat load can be removed with less energy costs (Brosnan & Sun, 2001). However, the SECT can be quite sensitive to oscillations in delivery air temperature in experiments, as the product temperature is now very close to this value, which is why the HCT is considered a more robust parameter to compare cooling times. In principle, the HCT and SECT can be assumed independent of the temperature difference $T_{p,0}$ - T_a (Eq. (1) (Brosnan & Sun, 2001)), which is evident from the idealised cooling curve (Eq. (2)). In practice, slight variations in HCT and SECT with ($T_{p,0}$ - T_a) will appear (Defraeye et al., 2014). Both HCT and SECT can be determined analytically from the cooling curve (Eq. (3)):

$$t_{7/8} = \frac{\ln(8j)}{C} \qquad ; \qquad t_{1/2} = \frac{\ln(2j)}{C} \tag{4}$$

Cooling rate

The cooling rate can be quantified by the cooling coefficient C [h^{-1}]. This coefficient (> 0) equals the magnitude of the (negative) slope of the ln(Y)-t curve. C is constant at any time for an idealised cooling curve. Alternatively, the cooling rate is sometimes quantified by the momentary (instantaneous) cooling rate (R_{tx} [°C h^{-1}]) at time t_x (Fraser & Eng, 1998; Thompson et al., 2008), defined as:

$$R_{tx} = C(T_{p,x} - T_a) = \frac{\ln(8j)}{t_{7/8}}(T_{p,x} - T_a) \tag{5}$$

where $T_{p,x}$ is the product temperature at t_x. The highest momentary cooling rate is found at the start of cooling R_0 [°C h^{-1}], thus where $T_{p,x}$ = $T_{p,0}$.

A more indirect measure of the cooling rate is the convective heat transfer coefficient (CHTC [W m^{-2} K^{-1}]) at the surface of the produce (Kondjoyan, 2006). CHTCs relate the convective heat flux normal to the surface ($q_{c,s}$ [W m^{-2}]), i.e., at the air-product interface, to the difference between the surface temperature ($T_{p,s}$ [°C]) and a reference temperature (T_{ref} [°C]), for which often the set air temperature (T_a) is taken: CHTC = $q_{c,s}/(T_{p,s}-T_{ref})$. The advantage of CHTCs is that they are rather independent of the magnitude of the heat transfer rate at the surface, as this is compensated by the temperature difference between product surface and cooling air. CHTCs can therefore be determined at very small temperature differences ($T_{p,s}-T_{ref}$), which make them useful quantities for transport and storage applications as well, in addition to precooling. Computational methods are preferred to determine CHTCs (Defraeye, Lambrecht, et al., 2013) as they cannot be quantified with high spatial resolution in most cold-chain experiments, thus not for every individual product in a box (Alvarez, Bournet, & Flick, 2003; Alvarez & Flick, 2007). Note that the magnitude of the CHTCs depends strongly on the choice of the reference temperature (T_{ref}), which becomes critical when comparing CHTCs.

3.1.2 Cooling uniformity

Uniformity (also homogeneity) of cooling between individual products within a box but also between individual boxes on a pallet or between pallets in a container is critical for ensuring uniform product quality and shelf life within each of these levels of packaging.

The spread on the cooling time (e.g., the standard deviation on the SECT) between individual products in a box, pallet or container can be used to reflect the heterogeneity at the packaging scale of interest (de Castro, Vigneault, & Cortez, 2004; Defraeye et al., 2014). Alternatively, the distribution of the CHTC between different products can be used. For CFD, CHTC information is even available for each computational cell on the product's surface (Defraeye, Lambrecht, et al., 2013).

The heterogeneity index for temperature was also used (HI_T, [%] (Dehghannya, Ngadi, & Vigneault, 2011)). This parameter compares the deviation of the instantaneous temperature in an individual product at a certain location (k) in the box ($T_{p,k}$) from the average temperature of all measured products ($\overline{T_p}$) at each point in time:

$$HI_{T,k}(t) = \frac{\sqrt{\left(T_{p,k}(t) - \overline{T_p}(t)\right)^2}}{\overline{T_p}(t)} \times 100 \tag{6}$$

Although Dehghannya et al. (Dehghannya et al., 2011) used the core temperature $T_{p,c}$ to calculate HI_T, other temperatures can be used as well. To avoid problems with this index when the product temperatures approach 0°C, as then the denominator is close to zero, it is advised to express the temperatures in degrees Kelvin.

3.2 Box ventilation

Box ventilation implies heat and mass transport within the air domain at all levels of packaging (polyliner bag, box, pallet, container). During precooling, proper box ventilation is critical to induce a sufficiently high and uniform cooling rate. During transport and storage, box ventilation determines the removal rate of respiration heat. In addition, it drives the distribution of metabolic gasses (O_2, CO_2, ethylene) and bio-active compounds within boxes, such as 1-MCP, to delay ripening of fruits (Ambaw et al., 2014; Ambaw, Verboven, Defraeye, et al., 2013a, 2013b; Ambaw, Verboven, Delele, et al., 2013). Box ventilation, either or not in combination with scrubbing, can play a key role in controlling the levels of metabolic gasses in a box (Wills, Harris, Spohr, & Golding, 2014). On the other hand, such ventilation will enhance the possible distribution of airborne spores and the resulting cross-contamination.

The box ventilation potential is mainly governed by the "accessibility" of the airflow to the produce, thus by the ventilation openings, but also by the complex airflow pattern through the dense stacking of products in the box. Box ventilation is often assessed qualitatively by assessing the spatial and temporal distribution of the airflow and scalars within the packaging but some quantitative performance parameters have also been set forth.

3.2.1 Ventilation potential

The airflow rate through a box or ensemble of boxes (Q_a) is widely used and is preferably expressed in L s^{-1} kg^{-1} of produce. These units make the airflow rate independent of the amount of fruit to be cooled, allowing a better comparison of airflow rates between for example large and small cooling systems. These airflow rates typically range from 1 to 3 L s^{-1} kg^{-1} for FAC (Brosnan & Sun, 2001; Thompson et al., 2008; Thompson, 2004) and 0.02-0.06 L s^{-1} kg^{-1} for refrigerated containers (Defraeye, Cronjé, Verboven, Opara, & Nicolai, 2015). Alternatively, the volumetric airflow rate (G_a) can also be used, which is expressed in m^3 s^{-1}. The number of air exchanges per hour (n [h^{-1}]) is often used to express the airflow rate for systems with a closed circuit, such as a refrigerated container or cold store (Ambaw et al., 2014; GDV, 2014). It is defined as the number of times per hour that the total volume of the enclosure is extracted by the ventilation system and sent back in.

The total open area percentage (TOA [%]) is frequently used in guidelines on packaging design as a measure for the ventilation potential. It is the amount of vent area relative to the total area of that specific side of the box. More detailed vent opening characteristics, such as size, shape, number and location, are inherently related to the TOA. The TOA is often correlated to the flow resistance of the box (pressure drop) and the related energy efficiency (de Castro et al., 2004, 2005b; Vigneault & Goyette, 2002; Vigneault, Markarian, da Silva Almeida, & Goyette, 2004) but also to the produce cooling rate (de Castro et al., 2004; de Castro, Vigneault, & Cortez, 2005a; Delele, Ngcobo, Getahun, et al., 2013b) and to the mechanical strength of boxes (J. Singh et al., 2008). This PP is clearly of interest for other package functionalities. Often the required (minimal) values for the TOA are specified, but also optimal values are reported, resulting from trade-offs with mechanical strength and energy efficiency. An overview of previously reported TOAs is given in Pathare et al. (Pathare et al., 2012).

3.2.2 Ventilation uniformity

A coefficient of variance C_v of the air speed distribution in a box or ensemble of boxes, packed with horticultural produce, has been used to describe the ventilation uniformity (Vigneault, de Castro, & Gautron, 2004). It is the ratio between the standard deviation (σ_U) of the air speed and its mean value (μ_U), based on multiple measuring points (de Castro et al., 2005a):

$$C_v = \frac{\sigma_U}{\mu_U} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(U_i - \overline{U}\right)^2}}{\overline{U}} \tag{7}$$

where U_i is the air speed [m s^{-1}] at a certain location in the air domain and $\overline{U}$ is the average speed over all monitored points. The air speed has also been inferred indirectly from product cooling rate measurements (de Castro et al., 2005a; Vigneault, de Castro, Goyette, & Markarian, 2007). Note that the standard deviation is a less accurate measure of variability if the distribution strongly deviates from a normal one (e.g. highly skewed), which is why the normality of the distribution should be verified.

The heterogeneity index for air speed (HI_U [%]) is similar to HI_T (Eq. (6)) (Dehghannya, Ngadi, & Vigneault, 2008) and compares the instantaneous velocity magnitude ($U_{i,k}$) at a certain location (k) with the average air speed of all (considered) measuring points ($\overline{U}$):

$$HI_{U,k}(t) = \frac{\sqrt{\left(U_{i,k} - \overline{U}\right)^2}}{\overline{U}} \times 100 \tag{8}$$

Other less-known heterogeneity indices for air speed or air temperature are the absolute deviation of the velocity magnitude (Delele, Ngcobo, Getahun, et al., 2013b) and the process capability index (Estrada-Flores & Eddy, 2006).

3.2.3 Bypass flow

Preferential airflow pathways, where air bypasses the produce, can occur due to improper stacking, the package design itself (Defraeye, Lambrecht, et al., 2013; Ferrua & Singh, 2009a, 2011; Vigneault & Goyette, 2003) or inadequate sealing of gaps with dunnage material (Fraser & Eng, 1998), such as the open air space between the pallets and the container door. In particular, packages of some fruit are not entirely filled to the top, by which a distinct headspace is present. Typical examples are found with kiwi fruit packaging or clamshells for strawberries. This headspace height (h_{hs} [m]) forms an important internal bypass which cannot be avoided by actions such as a-posteriori sealing.

Airflow bypass is not necessarily negative as this can imply that colder air reaches the boxes more downstream, which can improve cooling uniformity between boxes (Ferrua & Singh, 2011). Bypass can also relax the fan power needed to force air through the packaging, or allows to achieve higher air speeds. An internal bypass, such as via the headspace, is even deliberately foreseen in some cases to enhance heat transfer rates, even though this means much less fruit can be packed per m^3. This highlights yet another trade-off, namely between packing density and cooling efficiency.

Airflow short circuiting is dependent on the flow resistance of the produce-packaging system, compared to that of the bypass, but is quantified very rarely. This can be done by means of the percentage of air bypassing the produce (BP, [$kg_{air,byp}$/kg_{air}]), which was also termed air loss ratio (Vigneault & Goyette, 2003).

3.2.4 Closed vent openings of boxes

An amount of vent openings (horizontal or vertical) in the boxes can be closed due to stacking of boxes in layers, on a pallet or even by the (wooden) base of a pallet. Hence, stacking that does not result in the interlocking or aligning ventilations openings can reduce the box ventilation potential considerably. To quantify this blockage, a new parameter is introduced here: the blocked vent opening percentage (BVP [%]), defined as the area of blocked vent openings of the ensemble of boxes (A_{BV}) to the total open area of the boxes together in the direction of the airflow ($A_{TOA,tot}$): BVP = $A_{BV}/A_{TOA,tot}$. This parameter does not include blocking of vent holes by produce.

3.3 Product quality and shelf life

In contrast to most package functionalities (Table 2), the product quality, shelf life but also the amount of product being discarded along the way directly reflect the efficacy of the cold chain. Despite being key drivers for cold-chain optimisation, it is surprising how seldom these product quality parameters are included from the start in package performance evaluation (Table 1). Instead, they are often only evaluated for the "winning" prototype design. As research on food quality evaluation is vast (Laguerre, Hoang, & Flick, 2013), this section only highlights the efforts related to package design.

3.3.1 Product quality

Mass loss due to water evaporation (Δm [kg]) induces shrivelling of the product, stem dehydration and a direct loss of commercial value since several fruits and vegetables are sold on weight basis (Maguire et al., 2000; Ngcobo, Opara, et al., 2012). This mass loss and the reduction of external quality are heavily penalised by the market. Therefore, produce is exposed to high relative humidity environments but also (synthetic or natural) waxes and polyliner bags are used (Njombolwana et al., 2013). A related but more rare PP is the amount of condensation on the product (Van Der Sman, 1999).

Physiological disorders, such as chilling injury, are caused by postharvest stress applied to a product and result in external or internal symptom development, leading to reduced fruit quality and marketable value (Lafuente & Zacarias, 2006). In both citrus and kiwi fruit, these disorders are divided into non-chilling and chilling related. The latter are induced by too rapid cooling or too long exposure to low temperatures, which often occur close to vent holes. A chilling injury index (*CI*) is typically used to score the severity of the chilling injury lesions (Lafuente, Zacarias, Martínez-Téllez, Sanchez-Ballesta, & Dupille, 2001).

Fruit maturity, or the degree to which a product has ripened, is carefully controlled via the temperature in the cold chain. The degree of ripeness is often mirrored by its external colour, for example yellow vs. green for bananas. Colour can be quantified using a spectrophotometric or colorimetric measurement, or visually by classifying fruit into colour classes by means of colour charts (Jedermann, Praeger, Geyer, & Lang, 2014). Firmness measurements provide insight in the rate of softening and usually measure the pressure (P_{firm}, [N m^{-2}]) or force at collapse of the tissue. Other commercially-used maturity indices are the total soluble solids content (SSC, expressed as °Brix) and titratable acidity (TA).

Internal physical damage of produce during handling and transport includes impact (Bollen, Cox, Dela Rue, & Painter, 2001) and compression bruises (Chen, Ruiz, Fuming, & Kader, 1987), punctures (Desmet et al., 2004) but also abrasion damage due to vibrations (Berardinelli, Donati, Giunchi, Guarnieri, & Ragni, 2005). These can lead to external dark lesions which increase decay and quality loss. A recent review deals with quantitative evaluation of mechanical damage to fresh fruits (Li & Thomas, 2014) and details a multitude of performance parameters to quantify such damage. Packaging plays a critical role in mitigating the occurrence of such damage throughout the cold chain, for example by reducing contact through the use of formed trays.

Fruits can be infested with pests such as false codling moth or fruit fly, which can be quantified by the percentage of infested products per box (n_I [%]). Phytosanitary actions can be taken pre-harvest and between harvest and packaging, but additional fumigation (Walse et al., 2013) and/or cooling treatments (Hallman, Myers, El-Wakkad, Tadrous, & Jessup, 2013) are often applied post-packaging during transport and export. Packaging should, therefore, facilitate phytosanitary treatments, which implies allowing adequate cooling (Defraeye, Verboven, Opara, Nicolai, & Cronjé, 2015) and ventilation to introduce fumigants, while additional actions should be taken to keep the environment free from infection sources (Podleckis, 2007). Effectiveness of such treatments is measurable in terms of the amount of destroyed pests in infested fruit (Ke & Kader, 1992), but studies specifically in relation to package design are not known, to the best of the authors' knowledge.

3.3.3 Product shelf life

Product shelf life (SL [days]) is the time it takes before product quality drops below defined quality limits and therefore becomes unacceptable, after being exposed to specified storage conditions, i.e. the shelf life conditions (Tijskens, 2000). Shelf life can be expressed starting from any arbitrary point in the logistic handling chain, for example at harvest or at the point of sale. The end of shelf life is typically marked by the incidence of rots, storage disorders or by the fruit becoming overripe as generally indicated by its firmness or colour. Shelf life is an important factor to consider when commercialising products to satisfy consumer needs (Sloof, Tijskens, & Wilkinson, 1996). In a commercial environment, shelf life samples (also called retention or library samples) are often taken during long term storage, or prior to and on arrival of overseas transports, since they can help in identifying problematic shipments and stressful postharvest handling procedures (East, Trujillo, & Winley, 2010; East, 2011; Jabbar, East, Jones, Tanner, & Heyes, 2014). In the food industry this is commonly implemented in the form of accelerated shelf life tests to speed up the procedures (Pedro & Ferreira, 2006). In postharvest research, the inclusion of a shelf life period of one or two weeks at 18 °C after cold storage or transport is commonly applied. In the context of package design, shelf life is rarely assessed (Table 1, (Nunes, Nicometo, Emond, Melis, & Uysal, 2014)).

3.4 Mechanical strength of box

Boxes need to be sufficiently strong to protect the produce during handling, transport and storage. This strength requirement limits the amount of vent holes that can be provided (TOA) in a box made out of a given material, and also affects their size, shape and position. For cardboard packages, the box strength is also dependent on the relative humidity, which may strongly evolve over time and often includes high humidity environments. A lot of research has been done on the structural aspects of boxes (Frank, 2014; Pathare & Opara, 2014), but few research focussed on the impact of ventilation holes (Han & Park, 2007; Jinkarn, Boonchu, & Bao-ban, 2006; J. Singh et al., 2008). Currently, mechanical strength of ventilated packaging is evaluated based on very few performance parameters.

3.4.1 Compression strength and stacking strength

The compression strength is measured using box compression tests (BCT). BCTs evaluate the compressive force [N] versus the cross-head displacement [m] in a load-deflection curve (Frank, 2014). The compression strength is then defined as the peak force (F_{peak} [N]) or the peak force up till a pre-specified deformation distance ($F_{peak}(d)$). The latter is relevant as the position of produce in a box determines the maximum allowable deformation before compression causes damage to the produce.

The strength of boxes as stacked on a pallet can decrease throughout the cold chain due to handling damage and creep, particularly for corrugated fibreboard packages. The latter is caused by a prolonged stacking load at high relative humidities (Allaoui, Aboura, & Benzeggagh, 2009). The failure of a single box is already sufficient to compromise pallet stability. This stacking strength is usually not explicitly quantified, due to the lengthy and more complex experiments (Frank, 2014), but more research efforts are definitely welcome here. Instead a safety factor is added to the compression strength from individual box BCTs to account for the degradation effects (Twede & Selke, 2005). Note that the stacking arrangement on the pallet and tertiary packaging materials (e.g. cornerboards, strapping) can be used to enhance pallet stability.

3.4.2 Package cushioning

Packaging provides protection from shocks and vibrations during transport and handling. The resilience to shocks, so sudden increases and decreases in acceleration, is often quantified by evaluating the peak acceleration (a_{peak}) as a function of the static load (of a weight, σ [Pa]) for different drop heights (h), which leads to an ensemble of so called dynamic cushioning curves (Guo, Xu, Fu, & Wang, 2011; Guo, Xu, Fu, & Zhang, 2010; D. Wang, 2009). The peak acceleration is the ratio between the measured acceleration and the gravitational acceleration.

As vibration damage of produce often occurs at the vibration resonance frequency, it is necessary to perform vibration evaluation across a range of frequencies. Resilience to vibrations is therefore mostly quantified by evaluating the vibration transmissibility (VT, dimensionless) versus frequency (f_{peak}, [Hz]) for different static loads (weight, σ [Pa]) (Guo et al., 2011). As an alternative, the power density [m s^{-2} Hz^{-1}] versus frequency [Hz] has also been used (Jarimopas, Singh, & Saengnil, 2005).

3.5 Energy consumption related to package design

One way to optimise energy efficiency of the cold chain is to design more energy-smart packaging. In this review, this relates to the energy consumed by the ventilation system to maintain airflow through the boxes during precooling, transport and storage. Other package-related energy-efficient measures can be taken in packaging production, transport and recyclability (Opara & Mditshwa, 2013), but these are not covered here.

The energy required for fan operation and for removing the heat they produce is substantial (East, 2010): (1) during forced-air cooling, it can nearly equal the amount of energy needed for cooling the fruit (Thompson et al., 2010); (2) during long-haul transport in refrigerated containers, fans often run continuously at a relatively high power (e.g., ≈ 2 kW for a 40' refrigerated container with a total consumption of roughly 7-15 kW), which is why the largest energy savings in refrigerated containers are currently expected to lie in optimising fan operation (GDV, 2014); (3) during long-term storage, alternative on-off cycles and fan frequency control strategies are considered to reduce energy costs (East, Smale, & Trujillo, 2013). Package design has recently been put forward as one of the key factors to improve fan energy consumption (Defraeye et al., 2014; Ferrua & Singh, 2011; Thompson et al., 2010) but research on this topic is very limited to date. Only few energy-related package performance parameters exist, which are mainly related to FAC.

Fan energy consumption can be minimised by reducing the required fan power, by reducing the time needed to maintain this airflow and by increasing fan efficiency. As these three aspects are closely related to the package design (box geometry, vent hole configuration, total open area, stacking pattern on pallet, etc.), an understanding of the aerodynamic resistance of the produce-packaging system is of key importance.

3.5.1 Aerodynamic resistance

The aerodynamic (airflow) resistance of the produce-packaging system is expressed as the relation between the total pressure drop over the packaging (ΔP_t [Pa]) and the volumetric airflow rate through it (G_a [m^3 s^{-1}]):

$$\Delta P_t = \xi G_a^2 \qquad (9)$$

where ξ is the pressure loss coefficient ([Pa s^2 m^{-6}]or [kg m^{-7}]). This pressure drop only accounts for inertial effects (Forchheimer term). The viscous effects (Darcy term, ~ G_a) only become important at very low flow speeds (typically ~ 0.0001 m s^{-1} for refrigeration applications (Verboven, Flick, Nicolaï, & Alvarez, 2006)) and were found to be negligible for most horticultural cold chain applications. It should be noted that the total pressure (P_t) is the sum of the static pressure (P_s) and the dynamic pressure ($P_d = 0.5\ \rho\ U^2$, with ρ the air density [kg m^{-3}] and U the air speed [m

s^{-1}]). If the considered air speed upstream and downstream of the packaging is the same, P_d remains constant by which $\Delta P_t = \Delta P_s$ in Eq. (9) (ASHRAE, 2013).

The power required to push air through the packaging (P_w [W]) can be determined as (Defraeye et al., 2014; Ferrua & Singh, 2011):

$$P_w = \Delta P_t G_a = \xi G_a^3 \tag{10}$$

P_w only contains the contribution of the packaging and therefore the aerodynamic resistance of other system components has to be accounted for to determine the system curve (similar to Eq. (9) (ASHRAE, 2012, 2013)). The intersection of the system curve with the fan performance curve determines the corresponding working point of the system ($\Delta P_{t,wp}(G_{a,wp})$). The total power consumed by the fan ($P_{w,fan}$) can be calculated as: $P_{w,fan} = \Delta P_{t,wp}\, G_{a,wp}/(\eta_{fan}\, \eta_{motor})$. $P_{w,fan}$ also depends on the fan and motor efficiencies (η_{fan} and η_{motor} (Baird et al., 1988)) and is proportional to $G_{a,wp}^3$ (see Eq. (10)). The contribution of packaging to the system curve, so to the working point $\Delta P_{t,wp}(G_{a,wp})$ and to $P_{w,fan}$, can be substantial or even dominant. This is often the case for FAC (de Castro et al., 2005b), where the produce-packaging ensemble is one of the main resistances in the system. The fan energy consumption (E_{fan} [J]) can easily be calculated as $E_{fan} = P_{w,fan}\, t_{op}$, with t_{op} the operational time of the fan.

3.5.2 Package-related energy consumption

The package-related energy consumption (E_{pack} [J] (Defraeye et al., 2014; Ferrua & Singh, 2011)) is defined here as the energy required to force airflow through a box or an ensemble of stacked boxes. It is calculated by multiplying the corresponding power P_w (Eq. (10)) with the required (pre)cooling time (e.g., $t_{7/8}$).

$$E_{pack} = P_w t_{op} = \Delta P_t G_a t_{op} \tag{11}$$

E_{pack} only accounts for the contribution of the packaging and not of other system components or fan efficiency, which enables a direct comparison of the energy efficiency of different package designs, the amount of boxes or the stacking pattern. Such comparison by Eq. (11) does require knowledge of the individual working points (($\Delta P_{t,wp}(G_{a,wp})$), as illustrated further in section 5.2. E_{pack} can be quantified throughout all cold-chain unit operations (precooling, transport and storage).

3.5.3 System energy consumption

The energy added ratio (EAR) was proposed to measure the effect of box openings and airflow on the cooling system efficiency during precooling (de Castro et al., 2005b). It is defined as the ratio of the energy added during the cooling process (respiration energy E_r and ventilation energy E_v) to the initial energy that is stored in the produce at the start of precooling (field heat energy E_p):

$$EAR = \frac{E_r + E_v}{E_p} \tag{12}$$

The energy coefficient (EC) is a more system-related parameter (Thompson & Chen, 1988; Thompson et al., 2010). It is the ratio between the total sensible heat to be removed from the product (i.e. field heat) during (pre)cooling to the total electrical energy used to operate the cooling facility, thus for refrigeration equipment, lights and fans. As such, it can be considered as the coefficient of performance (COP) of the entire cooling facility (Thompson et al., 2010). (Thompson et al., 2010) observed that the ECs for FAC facilities did not improve significantly in a period of 20 years.

Compared to E_{pack}, the EAR and especially the EC are less transparent or sensitive to the contribution of the package itself, as multiple other factors also contribute. In addition, they can only be applied for precooling as they explicitly include the field heat.

4 Tools

Multiple experimental and numerical tools are available to analyse the various packaging functionalities and to quantify PPs (Table 2) throughout all unit operations of the cold chain. The state-of-the-art tools and their current limitations are discussed below according to each package functionality, instead of dealing with each tool separately. This choice was made since each functionality covers a different discipline: food engineers are concerned with fruit cooling and box ventilation, refrigeration engineers target system energy consumption, mechanical engineers look at strength of the package and postharvest physiologists deal with fruit quality and shelf life.

Previous reviews on such techniques for postharvest applications have covered experimental studies (Laguerre et al., 2013; O'Sullivan et al., 2015) and numerical studies, including CFD (Ambaw, Delele, et al., 2013; Dehghannya, Ngadi, & Vigneault, 2010; Norton & Sun, 2006; Norton, Tiwari, & Sun, 2013; Smale, Moureh, & Cortella, 2006; L. Wang & Sun, 2003). Others dealt with deterministic and stochastic modelling, specifically for thermal and quality evaluation (Hertog, Lammertyn, De Ketelaere, Scheerlinck, & Nicolaï, 2007; Laguerre et al., 2013) and with modelling of transportation systems (James, James, & Evans, 2006).

4.1 Product cooling

Product cooling time, rate and uniformity are quantified experimentally using laboratory setups, such as single pallet precoolers (Defraeye, Lambrecht, et al., 2013; Delele, Ngcobo, Getahun, et al., 2013a) or various types of windtunnels (Alvarez & Flick, 2007; Ferrua & Singh, 2009d, 2011; Kumar, Kumar, & Narayana Murthy, 2008; Lu, Dev, Vijaya Raghavan, & Vigneault, 2009; Vigneault, Goyette, & de Castro, 2006). In addition, full-scale experiments were performed in precoolers (Nunes et al., 2014), refrigerated containers (Defraeye, Verboven, et al., 2015; Jedermann, Geyer, Praeger, & Lang, 2013), refrigerated trucks (Hoang, Laguerre, Moureh, & Flick, 2012; Moureh, Tapsoba, Derens, & Flick, 2009) and cold stores (Nahor, Hoang, Verboven, Baelmans, & Nicolaï, 2005).

Product cooling is typically measured by monitoring the core temperature of the produce using a sensor inserted in the pulp. As an alternative to real products, produce simulators are applied to minimise (biological) variability within individual products and to increase repeatability (de Castro et al., 2005a; Dehghannya, Ngadi, & Vigneault, 2012; Delele, Ngcobo, Getahun, et al., 2013a; Lu et al., 2009; Vigneault & de Castro, 2005; Vigneault et al., 2006). Often plastic or metal simulators are used (Table 1), which however have largely different thermal properties than real produce. If no appropriate scaling is made, the predicted cooling behaviour will be significantly different. Simulators filled with a water-based solution (de Castro et al., 2004; Delele, Ngcobo, Getahun, et al., 2013a) are more suitable as the thermal properties are quite close to real fruit and vegetables, since these are mainly composed out of water.

Experiments on product cooling are very realistic as they include the effects of stacking imperfections or resulting gaps between boxes and as they operate under actual airflow and environmental conditions. The resulting variability in cooling behaviour however makes data interpretation more difficult and limits distinguishing the impact of small changes. The spatial resolution is also rather limited as only one or a few products are usually monitored per box or per pallet. Including more sensors is feasible but this increases the intrusive impact of the sensors on the flow field. These experiments are also costly, partially due to the produce’s cost. Therefore, replicate runs are scarcely pursued and even if they are, achieving the same delivery air and initial product temperature conditions is quasi impossible, leading to poor repeatability. The use of dimensionless variables (e.g. *Y*) filters out these variations to some extent.

As an alternative, numerical studies using CFD have become commonplace to analyse produce cooling behaviour throughout all cold-chain unit operations (Table 1). Next to monitoring the core temperature of every single product, CFD allows to track volume-averaged quantities (e.g., average product temperatures) and surface-averaged quantities (e.g., heat fluxes and CHTCs). Individual products in the boxes can be modelled discretely (Defraeye et al., 2014; Delele et al., 2008), where even a random produce stacking can be generated using the discrete element approach (Delele et al., 2008). Alternatively, the porous medium approach can be used (Alvarez et al., 2003; Alvarez & Flick, 2007; Ambaw et al., 2014; Ambaw, Verboven, Defraeye, et al., 2013b; Q. Zou, Opara, & McKibbin, 2006a). Although it is more simplified, less computationally expensive and allows larger ensembles of boxes to be modelled, it requires the empirical determination of pressure loss parameters, amongst others. This approach is detailed in-depth in several studies (Dehghannya et al., 2010; van der Sman, 2002; Verboven et al., 2006). Next to CFD, more simple zonal/nodal models have been used as well (Hoang et al., 2012; Laguerre et al., 2013; Tanner, Cleland, Opara, & Robertson, 2002; Tanner, Cleland, & Opara, 2002; Tanner, Cleland, & Robertson, 2002) as well as semi-empirical models based on the porous medium approach (Alvarez & Flick, 2007). Such numerical modelling inherently relies on detailed experimental validation to quantify model accuracy (Defraeye, Verboven, & Nicolai, 2013; Defraeye, Lambrecht, et al., 2013; Dehghannya et al., 2012; Delele, Ngcobo, Getahun, et al., 2013a; Ferrua & Singh, 2009d).

Future trends include, on the experimental side, monitoring of product cooling using wireless temperature sensor technology, such as by radio frequency identification (RFID) tags (Hoang et al., 2012; Jiménez-Ariza et al., 2014; Laniel, Émond, & Altunbas, 2011; Laniel & Émond, 2010; Z. Zou, Chen, Uysal, & Zheng, 2014). These sensors are however quite large compared to other sensors and are usually placed on the fruit or box surface rather than inside the fruit, as the signal attenuation within the products strongly limits the possible distance between sensor and receiver. This problem can be mitigated to some extent by message forwarding and the use of lower frequencies (Jedermann, Pötsch, & Lloyd, 2014). On the numerical side, there is a trend towards the use of more realistic 3D models for produce and internal packaging, for example from 3D scanning with computed tomography (Defraeye, Herremans, Verboven, Carmeliet, & Nicolai, 2012; Rogge et al., 2014). Trends also point towards multiscale approaches to cover cooling of individual boxes up to entire cooling facilities (Ambaw, Delele, et al., 2013; Ho et al., 2013).

4.2 Box ventilation

To assess box ventilation, knowledge is required on airflow and temperature patterns, their uniformity and the amount of bypass flow. For these purposes, CFD is often the preferred choice since high-resolution airflow measurements inside complex stacks of products are challenging. Typical problems are the positioning of sensors (e.g., hot-wire anemometer) and their intrusive nature. Also the large amount of measuring points needed to analyse airflow patterns and flow rates in detail is particularly challenging in commercial scale research. Non-intrusive techniques, such as laser diagnostics with particle image velocimetry (PIV) or laser Doppler anemometry (LDA), are an interesting alternative (Laguerre, Hoang, Osswald, & Flick, 2012; O'Sullivan et al., 2015). They are however not successful in measuring airflow within ensembles of packaged products as they need a clear line of sight. Even when transparent models for the box and produce are used, the refraction and reflection of the laser beam at the air-material interfaces make flow measurements quasi impossible.

A solution to measure flow inside complex configurations on a laboratory scale is applying the principle of refractive index matching (Wiederseiner, Andreini, Epely-Chauvin, & Ancey, 2011) in combination with non-intrusive imaging such as PIV. Here, the porous structure, for example a box with fruit, is made out of transparent material (epoxy, fused silica, silicone, glass, etc.). Instead of normal air, the working fluid is chosen so its refractive index matches that of the porous structure (water-glycerol, anisole, oil). As such, the porous structure becomes seemingly invisible within the fluid as no refraction occurs at the fluid-material interfaces. This enables flow measurements inside the structure with laser diagnostics. Experiments relying on the refractive index matching principle have been recently performed for flow inside fruit packaging (Ferrua & Singh, 2008, 2009c), but also for flow in porous foams (Butscher, Hutter, Kuhn, & Rudolf von Rohr, 2012), solid-liquid fluidized beds (Reddy, Sathe, Joshi, Nandakumar, & Evans, 2013) or in the nasal cavity (Hopkins, Kelly, Wexler, & Prasad, 2000). Most of the used fluids are quite viscous but some have viscosities similar to water. By applying Reynolds number scaling, the appropriate combination of working fluid, the size of the setup and the fluid speed can be determined for the specific cold-chain operation of interest.

Despite these interesting experimental developments, CFD still dominates box ventilation research (Table 1). It also plays a major role in research on optimisation of airflow and temperature fields in cold stores (Ambaw et al., 2014; Delele et al., 2009; Nahor et al., 2005) and transport equipment (Moureh & Flick, 2004, 2005; Moureh, Menia, & Flick, 2002; Moureh et al., 2009; Tapsoba, Moureh, & Flick, 2006, 2007). There is a trend towards more coupled multiphysics simulations, where in addition to heat and mass transport in the product, the package and the airflow, also moisture transport and other scalars are modelled (Ambaw, Verboven, Defraeye, et al., 2013b; Ambaw, Verboven, Delele, et al., 2013).

4.3 Product quality and shelf life

For product quality and shelf life evaluations, laboratory or field experiments are commonplace, also in the context of package design (Galić et al., 2011; Janssen, Pankoke, et al., 2014; Janssen, Schmitt, et al., 2014; Laguerre et al., 2013; Li & Thomas, 2014; Nunes et al., 2014). A recent development in this area is the use of online-monitored data (e.g., product temperature or environmental parameters) to predict product quality and shelf life evolution throughout the cold chain in real-time. This enables more intelligent logistics and shelf-life-based system operation (Giannakourou, Koutsoumanis, Nychas, & Taoukis, 2001; Hertog, Uysal, Mccarthy, Verlinden, & Nicolaï, 2014; Lütjen, Dittmer, & Veigt, 2012). Such online monitoring tools are particularly promising for export of fresh produce as they allow to control temperature and other operating conditions during the voyage to extend shelf life, but also to maintain compliance with phytosanitary protocols. Other recent developments include new sensor technology for ethylene (Janssen, Schmitt, et al., 2014) or mould detection (Janssen, Pankoke, et al., 2014).

Apart from the standard experimental techniques (Robertson, 2013), more advanced approaches are gaining interest, particularly non-destructive imaging, for example with X-rays or magnetic resonance imaging, (Defraeye, Lehmann, et al., 2013; Herremans et al., 2014; Nicolaï et al., 2014; Ruiz-Altisent et al., 2010; Van As & van Duynhoven, 2013). They are used to evaluate and quantify internal and external quality attributes of horticultural products, amongst others in the context of online quality inspection. These evaluation techniques are currently applied prior to packaging, but could in principle also be used further down the supply chain.

Regarding modelling, the deteriorative physical, (bio)chemical and biological processes which affect product quality and shelf life, are often described by simple kinetic models that depend on a few process parameters such as temperature or water activity (Hertog et al., 2014; Jedermann, Praeger, et al., 2014; Robertson, 2013; Van Boekel, 2008). These models are calibrated experimentally to determine the model constants and are often applied on their own (James et al., 2006; Van Boekel, 2008). However, there is a trend towards combining these quality models with deterministic heat and mass transport models covering both product and environment (Laguerre et al., 2013). In addition, different sources of variability can be incorporated via stochastic modelling techniques resulting in integrated deterministic-stochastic modelling approaches of the entire cold chain (Dabbene, Gay, & Sacco, 2008a, 2008b; Flick, Hoang, Alvarez, & Laguerre, 2012; Laguerre et al., 2013). So far, direct applications towards package design evaluation are, to the best of the authors' knowledge, non-existent.

4.4 Mechanical strength

Mechanical strength and integrity of boxes are mainly evaluated experimentally through the use of box compression tests (BCT), drop/impact tests and vibration testing, for which detailed standards are available (ASTM, 2008, 2010, 2013, 2014; Pathare & Opara, 2014; TAPPI, 2007, 2012). BCT can use both fixed or floating plates (S. P. Singh, Burgess, & Langlois, 1992). The latter allows to mimic the tilting effect often observed during failure as the plate can tilt. As such, it is more capable of identifying how a box might fail in real world situations. Drop tests can be performed constrained and free. Constrained drops utilise clamps to ensure the package impacts the floor at the correct orientation. Free drop tests release the box without restraints and are therefore more difficult to repeat consistently. A technique which combines the advantages of the constrained and free methods was recently developed (Goyal & Buratynski, 2000).

As an alternative to experimental analysis, the use of finite element modelling (FEM) has emerged for analysing the box material (Aslund, Hägglund, Carlsson, & Isaksson, 2012; Biancolini & Brutti, 2003; Haj-Ali, Choi, Wei, Popil, & Schaepe, 2009; Kueh, Navaranjan, & Duke, 2012) or the impact of vent-hole size, position and shape on box compression strength (Biancolini & Brutti, 2003; Han & Park, 2007). These FEM models often rely on mechanical properties of the box materials which are to be obtained from experiments. Both experiments and simulations looked at single boxes, which are often not filled with fruit. Future efforts should be directed towards transferring these results to relevant guidelines for entire pallets of boxes filled with produce in high RH environments.

4.5 Energy consumption related to package design

The aerodynamic resistance of the produce-packaging system, thus the ΔP_t-G_a relation (Eq.(9)), is essential to estimate the energy consumption related to package design (E_{pack}). It is also required to determine the system curve and is essential to derive the required parameters when using the porous medium approach (section 4.1). This resistance is usually quantified in a wind tunnel, by simply measuring the airflow rate and pressure drop over a box, a stack of boxes or even over internal packaging components (Delele, Ngcobo, Opara, & Meyer, 2013; Ngcobo, Delele, et al., 2012). Volumetric measurements of the airflow rate (orifice plate, large vane anemometer) are preferred over single point measurements of the airspeed (hot wire anemometer, pitot tube), as non-uniform airflow conditions and turbulence can induce inaccuracies. This ΔP_t-G_a relation can be inferred from CFD simulations as well (Defraeye, Lambrecht, et al., 2013). When combined with the cooling time, the energy consumption related to package design can be derived (Eq. (11)).

The EAR performance parameter requires the respiration heat and the working point of the system to be known (Eq. (12)). The latter implies knowledge of the system curve and fan curve. The EC needs to be determined experimentally, as it requires a direct measurement of the electrical energy usage. Future efforts could be directed towards splitting up the energy consumption of the entire system into its separate components (fans, compressor, etc.).

5. Trade-offs between package functionalities

The complex multivariate nature of package performance evaluation is illustrated by identifying several trade-offs between the package functionalities. First, a case study is presented on improving package design for forced-air precooling in the citrus cold chain. In addition, the relation of package design with ventilation system operation is highlighted, as this aspect remained largely unexplored so far. Both cases are used to prove that a more integrated analysis is essential to compare existing designs and to converge to improved package design.

5.1 Forced-air precooling of citrus fruit

Forced-air precooling is typically characterised by horizontal airflow, high flow rates, short duration and large installed cooling capacity. Defraeye et al. (Defraeye et al., 2014; Defraeye, Lambrecht, et al., 2013) evaluated two corrugated fibreboard box designs for citrus fruit: 'standard' and 'Supervent' (Figure 2a). These boxes have a TOA percentage along the short/long side of 2 %/1.5 % (standard) and 3.1 %/3.5 % (Supervent), respectively. Some performance parameters for the boxes are given in Figure 2b-e from these CFD studies (Defraeye et al., 2014; Defraeye, Lambrecht, et al., 2013) on a single layer of boxes. Additional experiments on chilling injury and moisture loss indicated symptoms of chilling injury for 24 % of the fruit in the standard box and for 12 % of the fruit in the Supervent box, and a slightly higher moisture loss for the fruit in the Supervent box. A comparison of all performance parameters is shown in Table 3.

From this integrated, multivariate analysis, the new Supervent box design outperforms the standard box for almost all PPs, except for moisture loss and mechanical strength, although the latter is still satisfactory. The superior performance of this type of carton resulted in its successful introduction and use in the South-African citrus industry. The pack-houses decided later on to remove the middle holes on the long side of the box, as these holes resulted in buckling of the boxes when handling them. The characteristic location of the vent holes at the edges of the Supervent box also appears in recent box designs for other types of fruit (apple boxes in Figure 1, banana box in Figure 1 and in (Jedermann, Praeger, et al., 2014)). The fact that such a design resulted from R&D efforts by different research teams also confirms the observed enhanced performance.

5.2 Fan operation in relation to package design

The impact that package design can have on the working point of the ventilation system is illustrated. Recall that the working point is the intersection between the fan curve and the system curve ($\Delta P_{t,wp}(G_{a,wp})$, section 3.5.1, Figure 3). The fan curve and fan efficiency highly depend on the fan characteristics and settings (axial, centrifugal, blade type, fan design, etc., (ASHRAE, 2012)). With variable speed fans, multiple fan curves can be attained by varying the RPM, often in a continuous way. The system curve, thus the $\Delta P_{t,system}$-G_a relation (ASHRAE, 2012, 2013), reflects the aerodynamic resistance of the entire system and includes the pressure losses over all its components which have to be compensated by the fan, such as the evaporator, ducts and packaging. The working point determines the airflow rate through the ensemble of boxes. It is, therefore, one of the main determinants for the produce cooling rate and box ventilation, but also for fan energy consumption and efficiency (section 3.5.1).

The impact of the produce-packaging system on the system curve and thus on the working point can be considerable. A typical example is precooling where the fan directly discharges into a cold room (Figure 1), since then little other airflow resistances come into play. The resistances that are encountered are strongly dependent on the precooling system type (Thompson et al., 2008). In refrigerated containers, other components within the refrigeration unit (e.g., ducts, heat exchanger) also contribute significantly to $\Delta P_{t,system}$, in addition to the packed produce in the container hold, due to the high air speeds in these components. Often the same (existing) cooling system (precooling, refrigerated container) is used for different packaging types, associated stacking and for multiple types of produce (fruits, vegetables and flowers). As such, these systems will operate at different working points.

Consider two similar package designs: a standard package and a new package design with a higher TOA and thus a lower flow resistance, such as Supervent (section 5.1, Figure 2a). Let's assume that the produce-packaging system contributes substantially to the system's aerodynamic resistance, which is often the case for FAC. Also assume that the cooling system was optimised for the standard package and that the fan RPM (thus fan curve) is kept the same for both boxes. The fan curve, system curves and corresponding working points (A & B) are shown in Figure 3. The airflow rate will be higher for Supervent and hence potentially also the produce cooling rate (Figure 2c). This will require a larger fan power ($P_{w,fan}$, section 3.5.1), especially if the fan efficiency at the second working point is also lower (point B' vs. A'). The resulting fan energy consumption (E_{fan}, section 3.5.2) is more difficult to predict as it is also influenced by the (lower) required cooling time. As such, introducing a more open package on an existing cooling system is not necessarily beneficial as complex trade-offs appear. The impact of such a change in working point when using a different package design is often overlooked.

On the other hand, if the fan RPM in the Supervent case is changed to match the same airflow rate as the standard box (point C), the Supervent's cooling rate should still be slightly superior (Figure 2c). The fan energy consumption will be much less, assuming that fan efficiency is independent on the RPM (both at point A'). Hence, for a new package design with improved product cooling and box ventilation characteristics, altering the fan settings can enhance at the same time system energy consumption.

In summary, different package designs need to be evaluated and compared at their respective working points, instead of at the same flow rate or pressure drop. The working point in turn has to be optimised for each specific package design. The low energy efficiency of FAC systems is often caused by improper design and operation of the fans (Thompson & Chen, 1988). Also for refrigerated containers, a high energy saving potential lies in the use of variable speed fans together with improved fan regulation (GDV, 2014). In addition, packages can have a significantly different airflow resistance (and working point) under horizontal (FAC, high flow rates) and vertical airflow conditions (container, low flow rates) (Defraeye, Cronjé, et al., 2015). In principle, an optimal package design should perform well for both cases, which implies trade-offs will probably have to be considered when designing the package.

6. Discussion

Package design and performance analysis are largely based on industrial trial-and-error. More in-depth experimental or computational studies are scarcer, although they clearly lead to new insights and substantial improvements to package design (Defraeye, Lambrecht, et al., 2013; Delele, Ngcobo, Getahun, et al., 2013b; Ferrua & Singh, 2009a). In addition, new objectives have recently surfaced in package design, such as system energy use, food losses but also energy, water and carbon dioxide emissions embedded in these losses. These drivers should help intensify future efforts on package performance analysis.

Towards an integrated approach

Future packaging should be designed by means of a more integrated approach to identify the several complex trade-offs at play, the most well-known being the delicate balance between maintaining the cold chain and assuring the mechanical integrity of both the package and product (Opara, 2011). Firstly, all relevant package functionalities have to be evaluated simultaneously (product cooling, box strength, product quality, system energy consumption, etc.), instead of only a few. First steps in this direction were made (Baird et al., 1988; Gwanpua et al., 2014). These authors however simplified the product cooling behaviour and did not explicitly account for packaging design. Secondly, all unit operations of the cold chain, with often different cooling characteristics, should be included. Such experimental and numerical supply chain research has been rather scarce (Dabbene et al., 2008a, 2008b; Jedermann, Praeger, et al., 2014; Rediers, Claes, Peeters, & Willems, 2009; van der Vorst, Tromp, & Zee, 2009). The main focus was on product cooling rate in combination with the product quality. Only Jedermann et al. (Jedermann, Praeger, et al., 2014) looked at packaging design to some extent.

It is not surprising that such complete cold chain analysis of multiple package functionalities over multiple unit operations has not been undertaken yet. It is a daunting task in which many trade-offs have to be identified and translated in an appropriate way into improved package design or enhanced cold-chain protocols. To this end, experimental and numerical expertise in several research fields is required, such as food engineering, postharvest technology, transportation technology, mechanical engineering and horticulture. Very few research teams or consortia possess such combined expertise and the associated experimental/numerical facilities. For this reason, researchers did not prioritise a holistic approach, but focussed in detail on one specific aspect of package design or on one specific unit operation.

Nevertheless, several tangible steps towards more integrated package design and cold chain evaluation can be made. One is to upgrade the existing engineering-economic model (Baird et al., 1988) by including highly detailed information on product cooling in relation to package design and addressing other unit operations of the cold chain as well. Another step could be to use CFD for optimising packaging aerodynamically (Defraeye, Lambrecht, et al., 2013) in combination with FEM (Han & Park, 2007) to simultaneously evaluate structural aspects.

Another holistic approach could lie in the evaluation of cold chains and packaging by using life cycle assessment (LCA) tools. LCA is used as a decision-support tool for food companies and policy makers to quantify and reduce the environmental impact along food supply chains (Cerutti et al., 2014; Hellweg & Milà i Canals, 2014; Stoessel, Juraske, Pfister, & Hellweg, 2012). Such LCA studies often focus on the agricultural (preharvest) stage (Pfister, Bayer, Koehler, & Hellweg, 2011; Sanjuan, Ubeda, Clemente, Mulet, & Girona, 2005) and lack detailed inventory data of postharvest unit operations (Sanjuan, Stoessel, & Hellweg, 2014). As an example, the energy consumption of a refrigerated container is assumed constant (e.g. (Stoessel et al., 2012)), although there is a dependency of the container's energy consumption on the type of cargo and packaging. In addition, the food losses along each unit operation and the embodied energy and resources therein are heavily simplified or not accounted for at all in many existing LCA studies. On the other hand, most LCA studies that specifically target packaging consider the packaging life cycle, but do not account for the impact which packaging has on product quality and losses (Albrecht et al., 2013). Such a limited scope of the assessment can lead to erroneous conclusions with respect to the optimal packaging design.

However, the experimental and numerical techniques discussed in this review allow to more accurately estimate product quality, shelf life and associated losses but also energy consumption and the role of the packaging therein. By feeding this information into existing LCA models, a more complete way becomes available to assess the environmental impact of packaging types and designs in the fresh produce supply chain.

Performance parameters

The final aim of more holistic package performance analysis is to come to an improved package design. To this end, the performance parameters can serve as useful quantitative measures to guide design decisions. Each PP can be given a certain weighting. Given the complexity of this multi-objective problem, the use of optimisation methods might be worthwhile to explore (Banga et al., 2008, 2003; East & Smale, 2008; Marler & Arora, 2004). Such methods increase the required expertise and resources, especially when combined with advanced numerical modelling such as CFD. Although one should be aware that an "optimal" package design actually does not exist, as it highly depend on the priorities set forth (i.e., the weighing factors), such optimisation methods can lead to clear design improvements.

An important issue needs to be raised regarding the use of reference values to calculate several performance parameters, such as the set air temperature to calculate Y (Eq.(1)) or the reference temperature to calculate the CHTC. For the CHTC, typical reference temperatures are, for example, the approach flow temperature, the bulk air temperature at the inlet of each row of boxes or the temperature at the vent holes of an individual box. Many discussions have been raised on which values should be taken for these reference values. The answer is clear: there is no correct choice. The reason is that all these performance parameters are quantities that are calculated a posteriori, specifically to quantify and compare some aspects of the cooling process. The choice of the reference value will however not affect the actual cooling process, but will just change the magnitude of the PP involved. The only critical point that should be kept in mind is that, when comparing such PPs (e.g. CHTC), the reference conditions are taken at the same location for all cases.

Intelligent logistics

Apart from altering packaging design, the cold-chain can also be improved in other ways. Recently, valuable contributions have been made with respect to intelligent logistics (Hertog et al., 2014; Jedermann, Nicometo, Uysal, & Lang, 2014; Lütjen et al., 2012). Here, the losses in the cold chain are reduced by monitoring fruit quality online throughout the cold chain, making associated predictions of remaining shelf life and using this information to improve logistics. In this context, concepts such as first-expired-first-out (FEFO) are being explored as an alternative for the current first-in-first-out strategy (FIFO). Such intelligent logistics rely heavily on wireless sensor technology, shelf-life modelling and warehouse scheduling optimisation. This approach aims primarily at optimising logistics for a given technology and cold chain, which can be by itself far from optimal. The present review on the other hand focussed on improving packaging and cold chain protocols/technology, as a strategy towards optimising food quality and losses.

7. Conclusions

Packaging can be considered one of the most cost-effective and flexible ways to improve the cold chain of fresh produce. This review dealt with the relevant packaging functionalities that should be covered in package performance analysis. These include product cooling behaviour, box ventilation, product quality and shelf life, mechanical strength of boxes and energy consumption of ventilation systems. Future efforts should be directed towards more integrated cold-chain analysis, in which all relevant package functionalities are evaluated simultaneously throughout all unit operations of the cold chain. A main contribution of this review is a summary of the package performance parameters (PPs) that are currently used to quantify these functionalities, a typical example being the seven-eighths cooling time. Such quantitative measures of package performance are essential to compare existing packaging designs or to evolve to improved designs using multivariate analysis and optimisation.

New developments in experimental tools for package performance evaluation include the use of more realistic produce simulators, wireless temperature sensor technology and non-intrusive imaging with laser diagnostics based on refractive index matching. On the numerical side, new advances include the use of realistic 3D geometrical models for produce, acquired from computed tomography or laser scanning. In addition, more complex multiphysics/multiscale models are developed to enhance predictions of transport processes in both the airflow and the produce. Finally, deterministic-stochastic modelling is explored to account for variability in product properties and environmental conditions.

The presented case studies highlighted some of the complex trade-offs that appear in package design, which only surface when applying an integrated evaluation across all its functionalities. Such a holistic approach towards packaging design can help in making future food cold chains more energy-smart and resource-efficient. The key message here is that packaging should be specifically designed for the cold-chain configuration that it will be used in, and that the system's operational parameters should be tuned to the specific package.

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Figure captions

Figure 1. Boundary conditions of the fresh-produce cold chain. (MAP: modified atmosphere packaging, COP: coefficient of performance. ([a] ©Sean Studio/Dreamstime.com, [b] ©Sedneva/Dreamstime.com, [c] ©Alexander Tolstykh/Dreamstime.com, [d] © Onion/Dreamstime.com, [e] (Delele, Ngcobo, Opara, et al., 2013), [f] (Ambaw, Verboven, Defraeye, et al., 2013a), [g] © Chiquita, h (Thompson et al., 2008), i (Moureh & Flick, 2004), j (Thompson et al., 2008)).

Colour for web only, black and white for print.

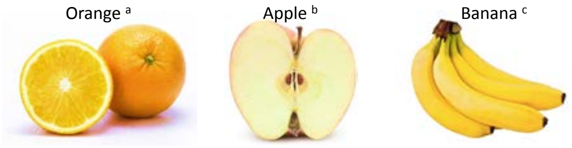
Figure 2. Comparison between standard (ST) and Supervent (SV) boxes for horizontal FAC from the CFD studies of (Defraeye et al., 2014; Defraeye, Lambrecht, et al., 2013) for different package functionalities: (a) geometry; (b) pressure loss as a function of flow rate and an indication of the blocked vent holes; (c) SECT ($t_{7/8}$) for each row of boxes as a function of both pressure difference and flow rate; (d) energy required to force airflow through the boxes until the SECT is reached as a function of airflow rate; (e) left: distribution of normalised convective heat transfer coefficients (CHTCs) over surfaces of oranges at a specific pressure difference, where the CHTCs are normalised with the surface-averaged CHTC over all oranges and all boxes, right: relative frequency distribution of the CHTC for each of the boxes in a layer, where CHTCs are scaled with the average CHTC per container.

Colour for web only, black and white for print.

Figure 3. System curves for two box designs and fan curves at two different RPM, including fan efficiency, with indication of working points.

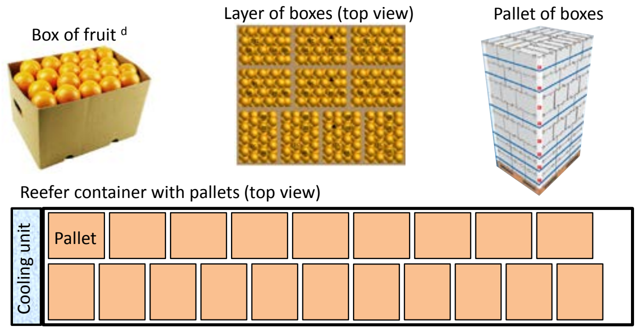
Colour for web only, black and white for print.

PRODUCT TYPE



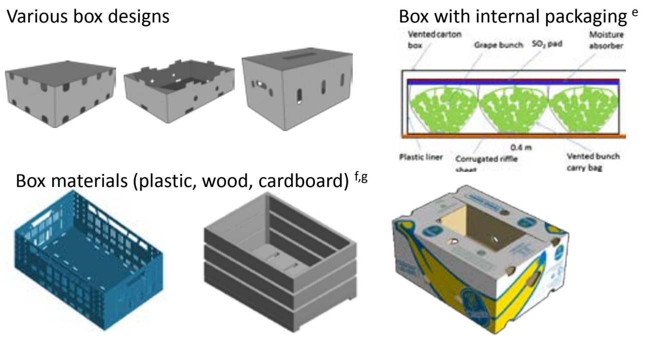
size, shape, climacteric/non-climacteric, respiration rate, transpiration rate, thermal properties (conductivity, freezing temperature, …), susceptibility to micro-/macrobiological infestation, …

STACKING



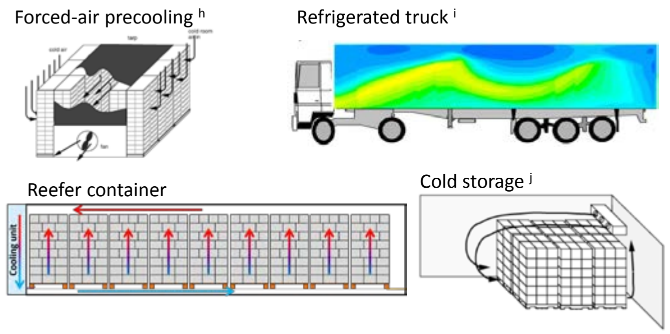
fruits in box (packing density), boxes on layer (amount and configuration), layers on pallet, pallets in container or storage room, space between pallets, loading density in cold store/container, …

PACKAGING



internal packaging (trays, polyliner bags, thrift bags, MAP), package footprint (geometry), material (cardboard, plastic, wood), vent holes (number, size, shape, position), thermal pallet covers, …

SYSTEM CONFIGURATION



precooling facility, reefer container and truck, cold store, display cabinet, …

SYSTEM SPECIFICATIONS

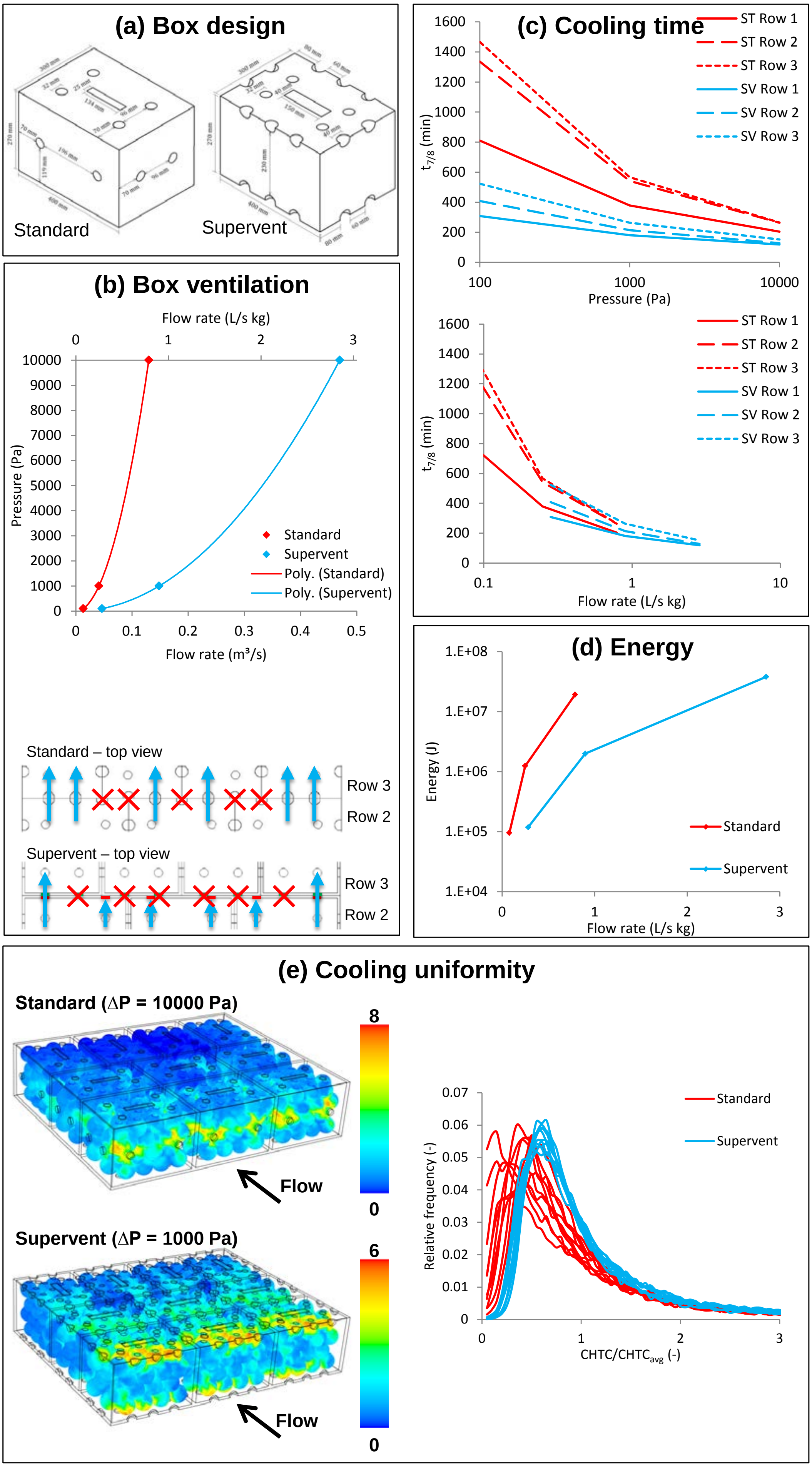
refrigeration capacity (power, COP), installed fans (airflow rate, pressure drop), air infiltration rate, thermal insulation (heat losses to outside), efficiency of components, airflow direction (horizontal: precooling, vertical: container, mixed: cold store & display cabinet), …

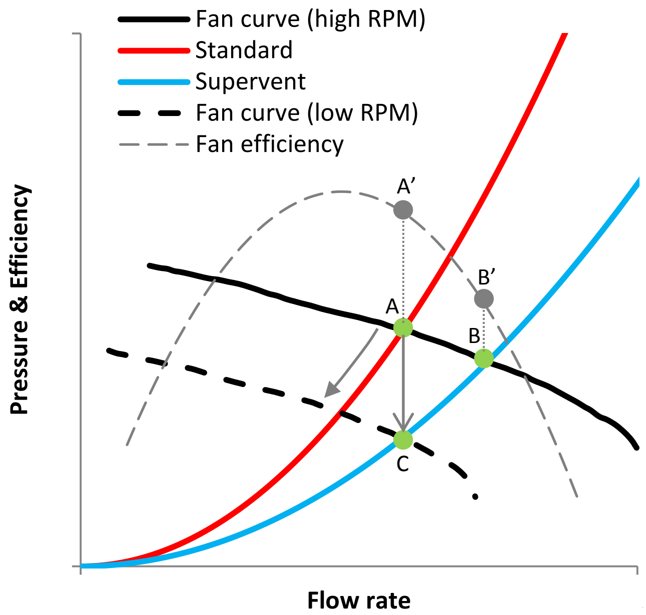
COLD CHAIN PROTOCOL

initial product temperature, cooling air temperature and relative humidity, airflow rate/speed, flushing/ventilation rate with fresh air, controlled atmosphere (CA), airflow scrubbing, regulations/legislation (produce temperature history, cold sterilisation treatment, export market), interruptions in cold chain, marketing requirements, …

HANDLING & TRANSPORT

environmental conditions (temperature, solar radiation), harvest time (day, night), transport time, transport route/way (maritime, air, train, road), treatments (degreening, waxing), …


(a) Box design
Standard
Supervent
(b) Box ventilation
Flow rate (L/s kg)
Pressure (Pa)
Flow rate (m³/s)
Standard
Supervent
Poly. (Standard)
Poly. (Supervent)
Standard – top view
Row 3
Row 2
Supervent – top view
Row 3
Row 2
(c) Cooling time
ST Row 1
ST Row 2
ST Row 3
SV Row 1
SV Row 2
SV Row 3
$t_{7/8}$ (min)
Pressure (Pa)
Flow rate (L/s kg)
(d) Energy
Energy (J)
Flow rate (L/s kg)
Standard
Supervent
(e) Cooling uniformity
Standard (ΔP = 10000 Pa)
Flow
Supervent (ΔP = 1000 Pa)
Flow
Relative frequency (-)
$CHTC/CHTC_{avg}$ (-)
Standard
Supervent



Fan curve (high RPM)
Standard
Supervent
Fan curve (low RPM)
Fan efficiency
A'
B'
A
B
C
Pressure & Efficiency
Flow rate

Table 1. Recent studies within the past decade (2004-2014) specifically focussing on package performance evaluation and design for the cold chain of fresh horticultural produce.

Reference	Method	Unit operation	Material	Package functionality									
				Product cooling		Box ventilation			Product	Mechanical strength	Energy consumption		Remark
				Rate/time	Uniformity	Ventilation potential	Uniformity	Bypass flow	Quality		Aerodynamic resistance	Fan/system energy cons.	
(de Castro, Vigneault, & Cortez, 2004)	Lab.	FAC	PVC & water-agar-filled spheres (PS)	HCT	Intrapack.	AFR					Correl.		Influence of TOA, number of vent holes, airflow rate.
(de Castro, Vigneault, & Cortez, 2005a)	Lab.	FAC	Polymer spheres (PS)	HCT	Intrapack.	AFR	CoV				-		Influence of TOA, number of vent holes, airflow rate. Air velocity at individual spheres was derived indirectly from HCT.
(de Castro, Vigneault, & Cortez, 2005b)	Lab.	FAC	Polymer spheres (PS)	HCT	Intrapack.	AFR	CoV				-	EAR	Influence of TOA, vent opening configuration, airflow rate. Focus on energy (EAR) and influence of produce respiration rate.
(Vigneault, Goyette, & de Castro, 2006)	Lab.	FAC	Polymer spheres (PS)	HCT		AFR	CoV				-	EAR	Influence of slat width in crates and airflow rate. Focus on energy (EAR) and influence of produce respiration rate.
(Zou, Opara, & McKibbin, 2006)	CFD	FAC	Apple (spheres)	Prod. temp.	Intrapack., Interpack.		AF pattern, temp. distr.						Model development and validation. Block structured meshing.
(Han & Park, 2007)	FEM & Lab.	-	Empty box							Comp. strength			Influence of size, shape, location of vent and hand holes
(Opara & Zou, 2007)	CFD	FAC	Apple (spheres)	Prod. temp.	Intrapack.	AFR							Influence of air speed, TOA, vent hole positioning, internal packaging (trays). Sensitivity analysis.
(Delele et al., 2008)	CFD & Lab.	FAC	Spheres			AFR	AF pattern				Correl.		Influence of stacking of products, product size, TOA, porosity, airflow rate. Discrete element method to generate random stacking of products.
(Singh, Olsen, Singh, Manley, & Wallace, 2008)	Lab.	-	Empty box							Comp. strength			Influence of size, shape, location, TOA of vent and hand holes
(Ferrua & Singh, 2009a)	CFD	FAC	Strawberry	CT	Interpack.			BPP					Influence of box design, TOA, reversal of airflow direction.
(Ferrua & Singh, 2009b)	CFD	FAC	Strawberry	Prod. temp.	Intrapack., Interpack.	Ind. AFR	AF pattern	BPP					Differences between individual boxes and individual fruit. Numerical model development.
(Ferrua & Singh, 2009c)	CFD & Lab.	FAC	Strawberry	Prod. temp., SECT	Intrapack., Interpack.		Temp. distr.		Moisture loss				Differences between individual boxes and individual fruit. Model validation.
(Tutar, Erdogdu, & Toka, 2009)	CFD	FAC	Spheres	CT, surf. flux.	Intrapack.	AFR	AF pattern, temp. distr.						Influence of airflow rate, inlet turbulence intensity, TOA. Focus on computational modelling aspects (mesh, turbulence modelling, 2D-3D model).
(Dehghannya, Ngadi, & Vigneault, 2011)	CFD	FAC	Polymer spheres	Prod. temp.	Intrapack. (HI)								Number of vent holes.
(Ferrua & Singh, 2011)	Lab.	FAC	Strawberry	Prod. temp., SECT	Intrapack., Interpack.	AFR	Temp. distr.				-	E_{pack}	Novel package system, based on airflow bypass. Influence of airflow rate, TOA.
(Dehghannya, Ngadi, & Vigneault, 2012)	CFD & Lab.	FAC	Polymer spheres (PS)	Prod. temp., CT	Intrapack. (HI)								Influence of number of vent holes, TOA.

(Ngcobo, Delele, Opara, Zietsman, & Meyer, 2012)	Lab.	FAC	Grape			AFR					Correl.		Influence of packaging components (box, carry bag, plastic liner).
(Ngcobo, Opara, & Thiart, 2012)	Full-scale	Room cooling	Grape	SECT					Multi.				Influence of packaging liners and their perforation.
(Ambaw et al., 2013)	CFD & Lab.	Cold storage	Apple				AF pattern, 1-MCP distr.		1-MCP adsorption				Influence of box material and 1-MCP dose on 1-MCP adsorption.
(Defraeye et al., 2013)	CFD & Lab.	FAC	Orange	Prod. temp., HCT, SECT, CHTC	Intrapack., Interpack. (CHTC)	AFR			Chilling injury				Different package design types. Intercomparison of experiments and CFD as analysis tools.
(Delele, Ngcobo, Getahun, et al., 2013)	CFD	FAC	Orange	Prod. temp., HCT, SECT	Intrapack.	AFR	AF pattern, Dev. veloc. & temp.				Correl.		Influence of airflow rate, TOA, vent shape, number and position.
(Delele, Ngcobo, Opara, & Meyer, 2013)	CFD & Full-scale	Room cooling	Grape	Prod. temp., HCT, SECT	Intrapack., Interpack.		AF pattern, temp. distr., RH distr.		Moisture loss				Influence of packaging components (carry bag, plastic liner) and box stacking. Analysis of alternative packaging and cooling procedures. Porous medium approach to model produce.
(Ambaw et al., 2014)	CFD & Full-scale	Cold storage	Apple			AFR	AF pattern, 1-MCP distr.		1-MCP adsorption, fruit firmness				Distribution and adsorption of 1-MCP in cool room. Influence of room shape, room packing density, box material, airflow rate, 1-MCP dose. Porous medium approach to model produce.
(Defraeye et al., 2014)	CFD	FAC	Orange	Prod. temp., HCT, SECT	Intrapack., Interpack. (CHTCs)	AFR					Correl.	E_{pack}	Evaluation of different package design types. Influence of airflow rate.
(Jedermann, Praeger, Geyer, & Lang, 2014)	Full-scale	Postharvest cold chain	Banana	Air temperature inside box	Interpack.				Colour				Use of spacers in boxes and chimneys between boxes. Remote monitoring during the cold chain.
(Defraeye, Cronjé, Verboven, Opara, & Nicolai, 2015)	CFD	Transport, FAC	Orange	Prod. temp., SECT, CHTC	Intrapack., Interpack. (CHTCs)	AFR							Comparison between vertical and horizontal airflow cooling performance. Impact of gaps between pallets.

Abbreviations

1-MCP distr.: distribution of 1-methylcyclopropene; **AF pattern**: airflow pattern; **AFR**: total airflow rate through system; **BPP**: bypass percentage; **CFD**: computational fluid dynamics; **CHTC**: convective heat transfer coefficient; **Comp. strength**: compression strength; **Correl.**: a correlation between pressure drop and airflow rate was determined; **CT**: cooling time, specifically defined in the study; **CoV**: coefficient of variance; **Dev. veloc. & temp.**: absolute deviations of velocity and temperature; **energy cons.**: energy consumption; **FAC**: forced-air cooling; **FEM**: finite element method; **Full-scale**: full scale experiment; **HCT**: half cooling time; **HI**: heterogeneity index; **Ind. AFR**: airflow rate through individual boxes of system; **Intrapack.**: uniformity between individual fruits in a single package; **Interpack.**: uniformity between different packages, e.g. on a pallet; **Lab.**: laboratory scale experiment; **Multi.**: multiple parameters were measured, namely moisture loss, stem dehydration, browning, SO_2 injury, decay, berry firmness, colour; **Prod. temp.**: product temperature history; **PS**: produce simulators; **RH**: relative humidity; **SECT**: seven-eights cooling time; **Surf. flux.**: heat flux at the surface; **Temp. distr.**: temperature distribution.

Table 2. Typical package functionalities and performance parameters used in package performance analysis.

Package functionality		Performance parameter (PP)	Symbol	Unit	Remarks
Product cooling	**Time**	Half cooling time, 7/8 cooling time	$t_{1/2}$, $t_{7/8}$	h (or s)	only for transient cooling problems (e.g., precooling)
	Rate	Momentary cooling rate	R_{tx}	°C h^{-1}	only for transient cooling problems (e.g., precooling)
		Cooling coefficient	C	h^{-1}	only for transient cooling problems (e.g., precooling)
		Convective heat transfer coefficient	CHTC	W m^{-2} K^{-1}	often expressed as correlation with air speed
	Uniformity (homogeneity)	Heterogeneity index (for temperature)	$HI_{T,k}(t)$	%	at a certain location k and point in time
		Distribution (spread) of CHTC over products	CHTC	W m^{-2} K^{-1}	
		Distribution (spread) of half cooling time or 7/8 cooling time over products	$t_{1/2}$, $t_{7/8}$	h (or s)	only for transient cooling problems (e.g., precooling)
Box ventilation	**Ventilation potential/rate**	Airflow rate	Q_a	L s^{-1} kg^{-1}	per kg of produce
			G_a	m^3 s^{-1}	volumetric
		Number of air exchanges	n	h^{-1}	closed circuit systems
		Total open area	TOA	%	highly relevant in other package functionalities
	Uniformity (homogeneity)	Coefficient of variance	C_v	-	
		Heterogeneity index (for air speed)	$HI_{U,k}$	%	at a certain location k and point in time
	Bypass flow	Bypass percentage	BP	%	also called air loss ratio
		Headspace height	h_{hs}	m	
	Closed vent openings	Blocked vent opening percentage	BVP	%	
Product	**Quality**	Moisture loss	Δm	kg	
		Chilling injury index	CI	-	different classes
		Fruit maturity (colour development)	Colour class	-	
		Fruit maturity (firmness)	P_{firm}	N m^{-2}	
		Fruit maturity (total soluble solids)	SSC	°Brix	
		Amount of products infested with pests	n_I	%	
	Stability	Shelf life	SL	days	
Mechanical strength	**Compression strength**	Peak force	F_{peak}	N	
		Peak force up till predefined displacement (d)	$F_{peak}(d)$	N	
	Shock resilience	Peak acceleration	$a_{peak}(\sigma,h)$	-	function of static load (σ) and drop height (h)
	Vibration resilience	Vibration transmissibility	$VT(f_{peak}, \sigma)$	-	function of peak frequency (f_{peak}) and static load (σ)
Energy consumption	**Aerodynamic resistance**	Pressure loss coefficient	ξ	Pa s^2 m^{-6}	relates pressure drop to airflow rate (ΔP_t - G_a)
	Package-related energy consumption	Package-related energy consumption	E_{pack}	J	
	System energy consumption	Energy added ratio	EAR	-	only for transient cooling problems (e.g., precooling)
		Energy coefficient	EC	-	only for transient cooling problems (e.g., precooling)

Table 3: Package functionalities and corresponding performance parameters that were evaluated for two citrus boxes.

Package functionality		Performance parameter (PP)	Best performance	Remark
Product cooling	Time	SECT	Supervent	Figure 2c. Note that it is a function of the working point.
	Uniformity	CHTC distribution	Supervent	Figure 2e
Box ventilation	Ventilation potential	Airflow rate	Supervent	Figure 2b
		Total open area	Supervent	
	Closed vent openings	Blocked vent opening percentage	Supervent	Figure 2b
Product	Quality	Chilling injury index	Supervent	results not reported
		Moisture loss	Standard	results not reported
Mechanical strength	Compression strength	Peak strength	Standard	From BCT using ASTM D642 protocols (ASTM, 2010)
Energy consumption	Aerodynamic resistance	Pressure drop vs. airflow rate	Supervent	Figure 2b
	Package-related energy consumption	Package-related energy consumption	Supervent	Figure 2d. Has to be evaluated together with fan curve.